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The Migration of Fluid Droplets and Their Interactions in a Thermal Gradient

R. S. Subramanian* and W. R. Wilcox

Department of Chemical Engineering

Clarkson College of Technology

Potsdam, New York 13676

When materials are processed in free fall, buoyant forces will be substantially reduced. Thus, the buoyant migration of droplets and bubbles which normally occurs on earth is expected to be overshadowed by migration due to other mechanisms in space processing. In particular, capillary forces on droplets due to the variation of interfacial tension around their periphery will play a significant role in governing their motion in space. While such interfacial tension gradients can be caused by thermal, compositional, and/or electrical gradients in the continuous phase, thermal gradients are convenient to use in controlled experimentation. On earth, due to interference from buoyant effects, it is difficult to study thermocapillary migration in sufficient detail. Also, the effects of a thermal gradient on the interactions among droplets are hard to study on earth. Thus, an orbital facility for conducting experiments on the migration and interactions of fluid droplets in a continuous phase due to the action of a thermal gradient appears attractive.

*Currently on sabbatical leave at Jet Propulsion Laboratory, Pasadena, CA 91103.

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In the space processing of materials, it is expected that many occasions will arise where liquid bodies containing droplets of a second fluid (liquid or gaseous) will be encountered. An example would be in the manufacture of space-processed glasses. In the glass production process, gas bubbles are formed due to chemical reactions as well as from gaseous pockets trapped in the interstitial spaces in the grains of the raw material. These bubbles have to be eliminated to produce usable glasses. Due to the reduction of the buoyant effect in orbiting spacecraft, the usual buoyant migration of such droplets or bubbles observed on earth will be reduced correspondingly, and their movement due to other forces will become important. Such movement will also have a significant effect on heat/mass transfer from/or to the droplet phase, and therefore needs to be characterized. It also is anticipated that in systems containing many droplets of a second phase, interactions among these droplets would be of great importance.

There are several mechanisms which would generate a force on a fluid droplet present in another fluid. There could be effects due to electric and magnetic fields. More subtle are the effects of a thermal or compositional gradient in the continuous phase. Such gradients on the droplet - fluid interface will usually result in interfacial tension gradients. An imbalance in the interfacial tension around the periphery of the droplet will result in traction being exerted on the neighboring fluids, the result of which is a net force on the droplet. The direction of this force is toward decreasing interfacial tension. Thus, gas bubbles in a temperature gradiant in a pure single-component liquid will migrate toward the hot end in the absence of other forces.

The fact that thermal gradients can cause the motion of gas bubbles has been quite well-known, and is illustrated in a film on the role of "Surface Tension in Fluid Mechanics" by Trefethan. An experimental demonstration as well as an approximate theory were provided by Young et al. (1959). These investigators held a small quantity of silicone oil between the anvils of a micrometer in which the lower anvil surface could be heated to different temperatures. The resulting vertical gradient of temperature

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exerted a force opposing the buoyant rise of gas bubbles in the column of silicone oil. By generating a sufficiently large thermal gradient in the liquid, Young et al. were able to arrest the buoyant motion of the bubbles and move them downward. They compared their experimental observations on the temperature gradient needed to keep a bubble stationary against buoyant forces with their theory, and noted reasonable agreement in spite of the scatter of the data. The thermocapillary force on a gas bubble in a thermal gradient was measured by McGrew et al. (1973) who used gas bubbles attached to a fine cantilever wire. Good agreement with the theory of Young et al. was found in ethanol while bubbles in methanol experienced a stronger force than that predicted by Young et al. This was attributed by McGrew et al. to the effects of volatilization and condensation at the opposite ends of the bubble. Recently, Hardy (1979) has performed careful experiments on bubble migration in a vertical temperature gradient. These experiments were conducted in a closed rectangular cell which eliminates the problems associated with the optical distortion through the cylindrical free liquid surface in the Young experiments. Perhaps more importantly, the absence of a free liquid surface avoids the thermocapillary convection which probably caused considerable scatter in the data of Young et al. Hardy's results for the vertical temperature gradient needed to arrest buoyant motion were in agreement with the theory of Young et al. The velocities observed were, however, somewhat lower than the theoretical predictions.

The types of experiments that can be performed on the migration of individual droplets or bubbles in a temperature gradient on earth are necessarily limited because of the presence of buoyant forces. The imposed thermal gradient has to be parallel or anti-parallel to the gravity vector. Any other thermal gradient (with a non-vanishing component in a direction normal to the gravity vector) always will result in buoyant convection in the fluid. This would strongly interfere with the interpretation of experimental data. Moreover, the theoretical problems of migration under the combined action of buoyancy and a temperature gradient in such situations becomes quite complex due to the loss of axisymmetry.

Even when a temperature gradient in the direction of the gravity vector is employed, there are severe constraints on the experiments that would be feasible on earth. If the temperature increases with height, the thermocapillary force would assist buoyancy and result in larger velocities, and hence, relatively small experiment durations. On the other hand, this situation usually results in a stable density gradient in the continuous phase far away from the droplet. It must be mentioned that in the vicinity of the droplet, lateral gradients of temperature cannot be avoided even though the fluid far away from the droplet is stably stratified. Because of the resulting lateral density gradients, it would be difficult to avoid buoyant convection contributions in the vicinity of the droplet.

The other alternative which still preserves axisymmetry and permits longer experimental times is the one used by Young et al. (1959) and by Hardy (1979). In these systems, the temperature decreases with height resulting in a thermocapillary force which opposes buoyancy. Thus, situations where

droplets/bubbles are slowed down in their rise, and even stopped and reversed can be achieved. However, in these experiments, there is an unfavorable density gradient in the continuous phase, and buoyant convection will set in when the Rayleigh number exceeds a critical value. Thus, there are severe upper bounds on the thickness of the fluid layer and the adverse temperature gradient which can be used since both of these quantities appear in the Rayleigh Number.

As indicated above, the presence of buoyant forces places serious constraints on the types of experiments that can be performed on earth on the migration of single bubbles or droplets in a thermal gradient. The problems are more severe when it is desired to study interactions between two or more such droplets in a thermal gradient on earth. Recent qualitative experiments (Mattox et al. 1978) indicate that such interactions may play a dramatic role in enhancing coalescence.

It would be desirable to have an orbital experimental facility available to study the motion of bubbles and/or droplets and their interactions in a continuous phase wherein a known thermal gradient can be imposed and maintained. While it is expected that compositional gradients in multicomponent systems will probably result in stronger capillarity-induced effects, a known steady thermal gradient can be established and maintained in a liquid with more ease than an analogous compositional gradient. The above facility would make it possible to study phenomena which are either difficult or impossible to study on earth. Due to the large reduction in buoyant forces, thermocapillary effects on larger droplets can be studied (without interference from buoyancy) than is possible on earth.

The experimental facility should provide for the convenient introduction of bubbles and/or droplets of various fluids of a variety of sizes in specific locations inside a continuous liquid phase. There should be arrangements for maintaining and measuring thermal gradients in the liquid. Also, provisions should be available for recording the positions and sizes of the bubbles and/or droplets through the duration of the experiments. It would also be desirable to be able to measure the temperature fields in the vicinity of the migrating droplets so that more detailed comparisons with theory can be made. It is quite possible that a specialized version of the "Fluids Experiment System" would be an apropriate apparatus for performing these experiments.

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